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ROADWAYS AND INFRASTRUCTURE

Life cycle assessment in road infrastructure planning using spatial geological data

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Abstract

Purpose The purpose of the study was to outline and demonstrate a new geographic information system (GIS)-based approach for utilising spatial geological data in three dimensions (i.e. length, width and depth) to improve estimates on earthworks during early stages of road infrastructure planning.

Methods This was undertaken by using three main methodological steps: mass balance calculation, life cycle inventory analysis and spatial mapping of greenhouse gas (GHG) emissions and energy use. The mass balance calculation was undertaken in a GIS environment using two assumptions of geological stratigraphy for two proposed alternative road corridors in Sweden. The estimated volumes of excavated soil, blasted rock and filling material were later multiplied with the GHG emission and energy use factors for these processes, to create spatial data and maps in order to show potential impacts of the studied road corridors. The proposed GIS-based approach was evaluated by comparing with actual values received after one alternative was constructed.

Results and discussion The results showed that the estimate of filling material was the most accurate (about 9 % deviation from actual values), while the estimate for excavated soil and blasted rock resulted in about 38 and 80 % deviation, respectively, from the actual values. It was also found that the total volume of excavated and ripped soils did not change when accounting for stratigraphy.

Conclusions The conclusion of this study was that more information regarding embankment height and actual soil thickness would further improve the model, but the proposed GIS-based approach shows promising results for usage in LCA at an early stage of road infrastructure planning. Thus, by providing better data quality, GIS in combination with LCA can enable planning for a more sustainable transport infrastructure.

Keywords Energy · Geology · GHG emissions · GIS · LCA · Mass balance · Road · Stratigraphy

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1 Introduction

Environmental impacts during the life cycle stages of transport infrastructure are substantial, including among other greenhouse gas (GHG) emissions, as well as resource and energy use. For transport infrastructure to be sustainable, such issues need to be integrated in the planning process. Transport infrastructure project planning is a complex process that can last for decades (Arts and Lamoen 2005). According to the Swedish Transport Administration (STA), this planning is implemented stepwise at different levels from national to regional scale (STA 2011). Miliutenko et al. (2014a) identified three main levels of decision during the transport planning: (1) choice of transport modality at the national level, (2) choice of road corridor and construction type of a specific project and (3) choice of specific construction design. The first level of planning is also known as strategic planning in Sweden (Miliutenko et al. 2014a). During the strategic planning, it is decided whether there is a need to construct a new road or if any other mode of transportation is more suited (Kluts and Miliutenko 2012). If it is decided to construct new road infrastructure, then decisions on the most suitable location for the road corridor and construction type are made. Finally, a specific construction design is chosen. This could be for instance the choice of specific material used for construction and stabilisation methods needed (Miliutenko et al. 2014a).

The choice of road corridor location, in this paper referred to as an early stage of road infrastructure planning, has a great effect on further environmental impacts that arise during road construction, operation and maintenance. Such choices determine the type of road infrastructure element needed (e.g. tunnels, bridges and/or plain roads) and influences the future emissions from traffic. According to Energy Conservation in Road Pavement Design, Maintenance and Utilisation (ECRPD 2010), energy savings of up to 47 % in road construction, up to 20 % in road operation and up to 30 % in road maintenance can be achievable if the energy implications of a road alignment are evaluated in the early planning stages of a project. Thus, conflicts of interest and expensive environmental measures in later phases can be avoided if all necessary aspects are considered at an early stage (STA 2011).

Performance of Environmental Impact Assessment (EIA) is required by the European Union (EU) in order to ensure that all environmental aspects are considered during planning of the road infrastructure project (EC 2012). As a part of this process, the European Commission (2013) suggested the use of the tool life cycle assessment (LCA) for assessing life cycle energy use and GHG emissions. LCA is a tool for analysing life cycle impacts of a product or system during its whole life cycle: from raw material extraction through production, use and waste treatment or final disposal (ISO 14044 2006). It can be used for assessment of various environmental aspects during the life cycle stages of road infrastructure (Loorents 2006).

Several LCA models have been developed to assess the impacts of road infrastructure during different stages of road infrastructure planning. For instance, Dubocal (van't Wout et al. 2010), LICCER (Brattebø et al. 2013), CEREAL (2014), EFFEKT (Straume 2011), Joulesave (ECRPD 2010), Klimatkalkyl (STA 2015) and RoadRes (Birgisdóttir 2005) are among several models that have been developed in Europe. As described in Miliutenko et al. (2014a), models such as Dubocal, CEREAL and RoadRes were developed for later stages of road infrastructure planning, where more detailed design of the road is known. The models that have been specifically designed for the earlier stages of planning (i.e. the choice of road corridor) are EFFEKT, Joulesave, Geokalkyl, Klimatkalkyl and LICCER. Except Klimatkalkyl, all the other models mentioned above were developed only for road infrastructure, while Klimatkalkyl also assesses railway infrastructure (STA 2015). These models are also different in terms of system boundaries and impact categories included.

Case studies performed by the models LICCER, Joulesave and Dubocal have shown that the highest share of energy use and GHG emissions comes from traffic operation when studying the total impact from a road transport system (Liljenström 2013; Shamoon 2012). However, when analysing life cycle impacts of the road infrastructure itself, earthworks and materials used for the road construction have a big share in the total energy use and GHG emissions (Garbarino et al. 2014; Hammervold et al. 2009; Liljenström 2013). Those aspects are largely determined by geological conditions at the site of construction: parameters such as soil thickness, slope, bedrock quality and soil type. The geological parameters determine the amounts of earthworks (i.e. volumes of soil and rock that will be excavated and blasted), transportation needed for the excavated materials as well as availability of building materials. Information about these geological parameters can be found in spatial geological data, and this information can be utilised through geographic information systems (GIS). GIS can store large volumes of multidisciplinary datasets for specific locations and can be used to derive new information through empirical statistical analysis, mechanistic process models or rule-based logic models (Geyer et al. 2010).

Existing LCA models for early road infrastructure planning rely on either default values for a typical area or a typical road or on expert estimations based on previous experiences. For instance, the model Klimatkalkyl includes default values on excavation based on predicted measurements for road sections in the specific road project Stockholm Bypass (Förbifart Stockholm) (STA 2015). However, the volumes of excavated soil and rock differ widely depending on the specific location or section of the road. For instance, the values for excavated soil for construction of a four-lane road at Stockholm Bypass differed in different locations along the road from 14,000 to 85,000 m^3/km, while the volumes of excavated rock differed from 0 to 130,000 m^3/km (STA 2015). Due to the high variability of data for different parts of the road within a project, the use of such default values can be questioned. It is important that the estimates of earthworks are close to real values for the specific road stretch, in order to make a comparative LCA of the road corridor alternatives as fair as possible. The reliability of such estimates could be improved by utilising the extensive site-specific information available through existing spatial geological data and models based on GIS. However, there is a need for development of methods for the integration of spatial data from GIS-based models with LCA models.

The use of LCA with GIS has previously been studied in different areas. Discussions of integration of LCA can be found in Bengtsson et al. (1998), who presented a data model of the LCA procedure which included geographical information for assessing site-specific impacts. However, the process of actual integration has been slow since that time (Geyer et al. 2010). Several studies that integrated LCA with GIS were focused on the production of biofuels from energy crops (for instance, Gasol et al. 2011, Dresen and Jandewerth 2012, and Geyer et al. 2010). Blengini and Garbarino (2010) presented a model where LCA and GIS were combined for analysing environmental implications of the construction and demolition waste recycling chain, while Azapagic et al. (2007) presented an integrated life cycle methodology for spatially mapping pollutants in the urban environment from sources through the environment to receptors.

The model Geokalkyl v.2 that is currently being developed in Sweden couples LCA with GIS and is aimed to be used during early stages of road infrastructure planning. Geokalkyl has been specifically developed to estimate cost, energy and CO_2 emissions due to earthworks and geotechnical stabilisation (STA 2016). However, the model is still in the phase of development and no detailed information has been published so far. No other studies using the coupling between LCA and GIS for early road infrastructure planning have been found to the best of our knowledge.

The overall aim of this paper was to outline and demonstrate a new approach for utilising spatial geological data in three dimensions (i.e. length, width and depth) to improve estimates of earthworks in LCA of road infrastructure during early stages of road infrastructure planning (i.e. choice of location of the road corridor). This was undertaken in a GIS environment using two assumptions of stratigraphy in order to estimate the mass balance for each road corridor alternative, which was further used in the LCA calculations. The proposed GIS-based approach for mass balance estimation was tested in a case study, in which the energy use and GHG emissions due to earthworks (soil excavation and rock blasting) for alternative road corridors were estimated. The accuracy of the proposed GIS-based approach was evaluated by comparing with real values of masses provided for the road corridor alternative that was actually built.

This study included only specific activities of road construction which are dependent on geological conditions of the road. These activities concern earthworks, such as soil excavation, rock blasting and filling (terracing) by excavated soil and blasted rock. Other processes during road infrastructure construction (such as for instance, removal of vegetation, soil stabilisation and construction of different layers of the road) were excluded from the analysis.

2 Study area and case study

The case study was the reconstruction project of Road Object 55 located in the southeast of Sweden (between Yxtatorpet and Malmköping). This project included three road corridor alternatives (Fig. 1). Due to previous evaluations of this

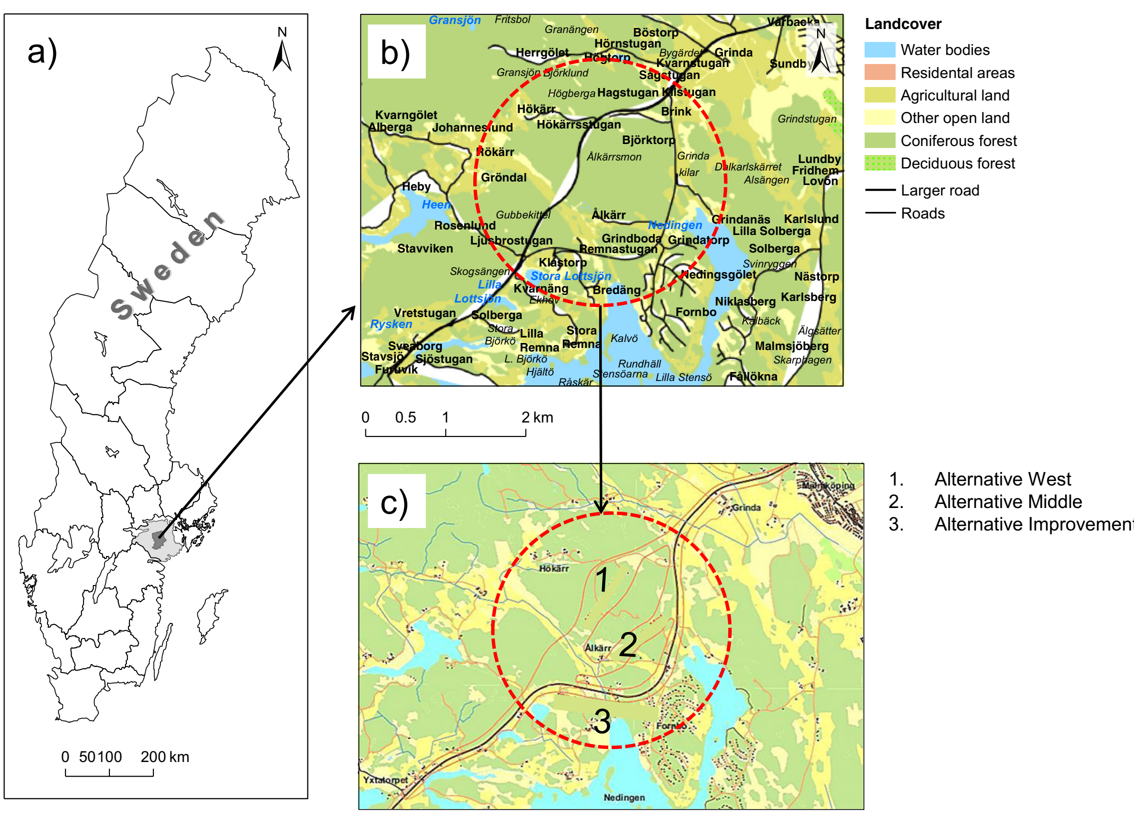


Fig. 1 **a** Map of Sweden with its national and county borders, **b** location of the study area and **c** the location of the different route alternatives assessed in the planning of the road (STA 2006). Spatial data © Lantmäteriet i2015/920, coordinate system Sweref 99 TM

project (i.e. Shamoon 2012; Liljenström 2013; Miliutenko et al. 2014b), there was good availability of data for verification of the results. Moreover, this project has already been constructed, which enabled a comparison between the estimates of volumes of rock and soil with the real updated values from the construction of one of the alternatives.

The study area is situated in the municipality of Flen, approximately 100 km to the west of Stockholm city (59° 7 N, 16° 40 E). This part of the country and especially Road Object 55 has an important role from a national, regional and local perspective (STA 2014). Road Object 55 diverts long distance transportation from going through the capital Stockholm (STA 2006), which already suffers from traffic-related issues such as congestion and high particle values. However, Road Object 55 had a poor standard, i.e. it is narrow and winding with few possibilities of overtaking, compared to the expected future needs. Several fatal accidents had occurred due to poor visibility at certain places, which, along with the overall low standard, reduced the maximum speed to 70 km/h. It was therefore stated by the STA that improvements along this route would benefit the area and the long distance transportation (STA 2006).

Minimum and maximum elevations in the study area are 23 and 79 m, respectively (Fig. 2a). The main soil type in this region is till followed by clay and rock (Andersen and Borns 1997; Flint 1971) (Fig. 2b). The bedrock is predominantly a quartz-feldspar-rich metasedimentary rock (Fig. 2c) that generally has a gneiss characteristic, i.e. meta-greywacke, meta-argillite and paragneiss. In the northeast and southeast, there are a few clusters of felsic intrusive rocks composed of granitoid gneiss. In the northwest, a small cluster of ultramafic, mafic and intermediate intrusive rocks, i.e. diabase, meta-diabase, and amphibolite, can be found.

The part of the road that was analysed in the case study is approximately 7.5 km long. To meet the demands on technical standard, it was decided that the road had to be widened from 9 to 14 m and the plan and profile geometry adjusted. The road was planned to have the standard of a 2 + 1 road, i.e. a specific category of roads with three driving lanes, where two lanes go in one direction and one lane in the other direction (STA 2006).

In order to choose the most suitable road corridor, three alternatives for new road construction projects and a zero alternative (i.e. no new construction) were compared during the road planning (Liljenström 2013). Estimates of blasted rock and excavated soil were compared for the three alternatives during planning of the new road stretch and reported in an Environmental Impact Statement (EIS), which is the document that was developed during the EIA for the feasibility study and choice between the alternative road corridors (STA 2006).

Two of the original road corridor alternatives were chosen for the case study: *Alternative West* and *Alternative*

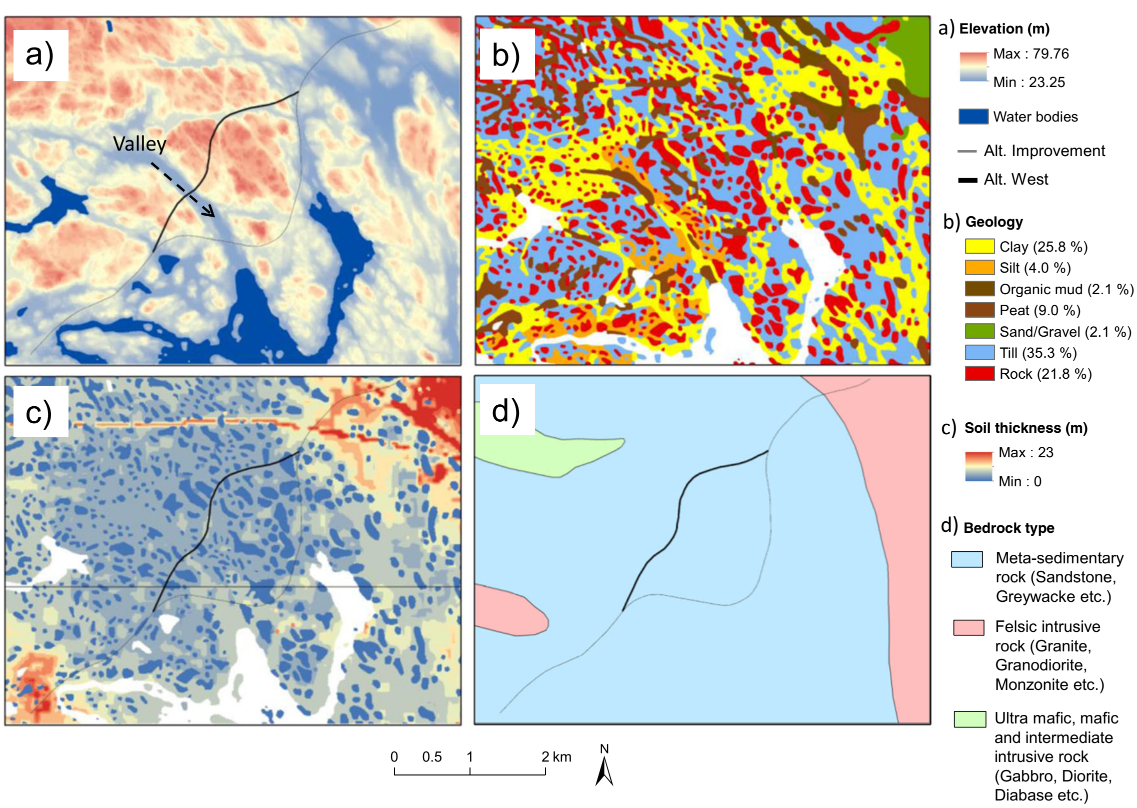


Fig. 2 **a** Digital elevation model (DEM), **b** geological map with soil and rock outcrops, **c** soil thickness map and **d** bedrock type map used for estimating bedrock quality. Spatial data © Lantmäteriet i2015/920, © SGU (2015), coordinate system Sweref 99 TM

Improvement. *Alternative West* was chosen for the analysis as it was preferred by the planners and selected for the actual road construction (Fig. 3). Since construction of this road was recently finalised, this alternative gave the possibility to compare estimates of volumes of excavated soil and blasted rock using GIS as well as Klimatkalkyl in this study with the volumes from the actual construction of the road. *Alternative Improvement* was used for comparison with *Alternative West*. However, estimated volumes for *Alternative Improvement* could only be compared with the estimates reported in the EIS (STA 2006). Below follows a brief description of the two alternative corridors. A more detailed description is provided in Liljenström (2013).

- *Alternative Improvement*: This involved a reconstruction of the existing road by widening and straightening the road and making adjustments to the road profile. The length of the road is approximately 7.5 km.
- *Alternative West*: The beginning and the end of the road were reconstructed in the same way as described for *Alternative Improvement*. This alternative included the construction of a new road stretch approximately 3.0 km long, the extension of the road in the start and end section of approximately 3.6 km as well as a new bridge (20 m). The total length of the road is approximately 6.6 km. Use of bridges or potential tunnels was not included in this study.

3 Materials and methods

3.1 Conceptual model

The conceptual model for the proposed GIS-based approach for mass balance estimation of the two road alternatives and its integration within the LCA methodology can be seen in Fig. 4.

Fig. 3 Alternative West after the construction was finalised. Photo © Sofiia Miliutenko

Three main steps were performed in this study: (1) mass balance calculation, (2) life cycle inventory analysis and (3) spatial mapping of GHG emissions and energy use (Fig. 4). Firstly, GIS was used to calculate the need for cut and fill (mass balance), with and without using stratigraphical information, during construction of the studied alternative road corridors (Section 3.2). Secondly, the estimated volumes were used as input in GIS where the total energy use and GHG emissions were spatially allocated by multiplying the volumes of excavated soil, blasted rock and filling material with emission factors for these processes (Section 3.3). This was done in order to evaluate the spatial distribution of the potential energy use and GHG emissions during soil excavation, rock blasting and filling in each alternative road corridor. As a result, energy use and GHG emission maps were created in order to show these values in each location corresponding to the area of 1 m^2 (i.e. 1 × 1 m pixels) of the studied road corridors (Section 4.2).

3.2 Mass balance calculation

3.2.1 Topographical and geological data used for mass balance calculations

The data that were used in this study for estimation of mass balance consisted of (i) geological data with information about the spatial distribution of soil types and existence of rock outcrops, (ii) bedrock data containing information about the distribution of rock type along the study area, which was used for estimation of bedrock quality, (iii) a digital elevation model (DEM) containing information about terrain elevation and (iv) property data containing information about buildings, roads and property boundaries. For more detailed information about the geological data used in this study, see Table 1.

The DEM (Fig. 2a) was resampled to 1 m horizontal resolution (from the original 2 m horizontal resolution) in order to enable an easier mass balance calculation. From this data, information about the difference in elevation (per individual raster cell) depending on assumed average embankment height could be retrieved, as well as the corresponding cut and fill needs.

The soil map (Fig. 2b) was reclassified in order to group all the different types of soil and rock types into three categories according to ECRPD (2010) (Fig. 5):

1. Soils for excavation: This category included clay, sand, gravel, silt as well as peat and other organic soils.
2. Rock and soil that require ripping before excavation: This category included very hard and compact overburden, which in this study was restricted to till.
3. Rock for blasting: This category included rock of any type.

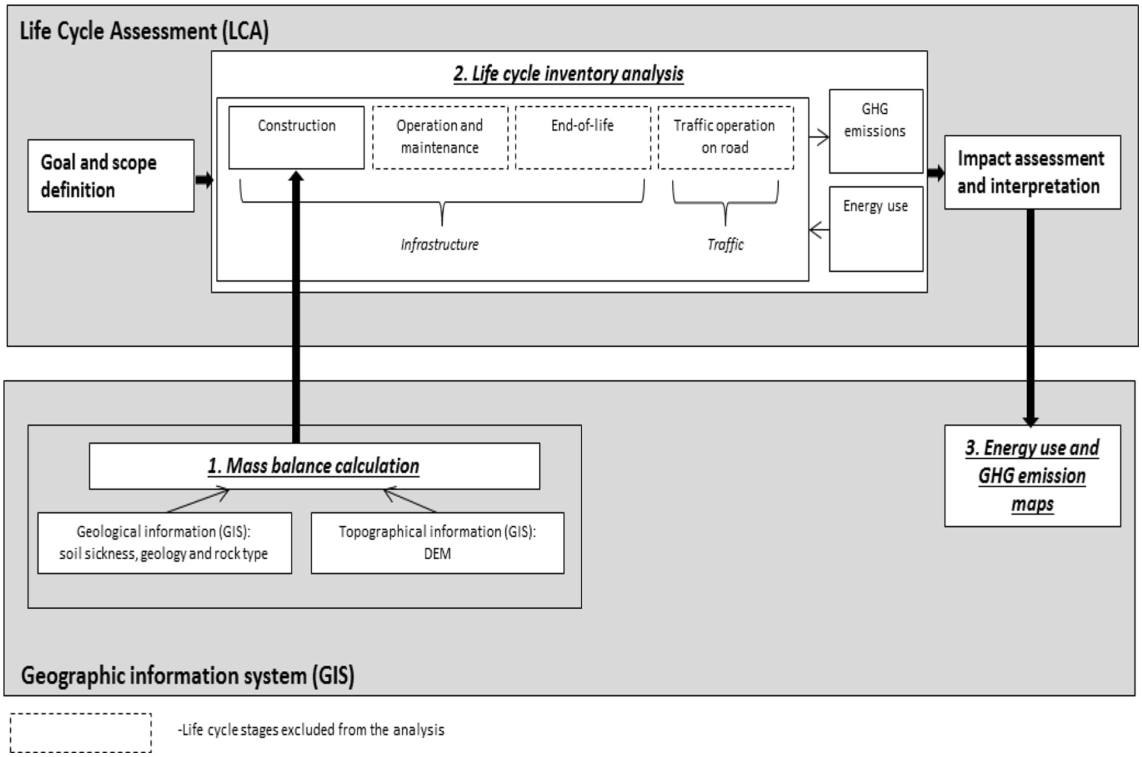


Fig. 4 A conceptual model of the proposed GIS-based approach and its integration within LCA (after Geyer et al. 2010)

The soil thickness (Fig. 2c) was estimated by using a model developed by the Geological Survey of Sweden (SGU) (Daniels and Thunholm 2014). This model is based on inverse distance weighted interpolation of point data with soil thickness information from both geotechnical investigations and groundwater well installations and created by separately interpolating each soil type (except organic soils) and merging the interpolations together. It was used in this study *as is*, meaning no alterations were done to the soil thickness model.

The bedrock quality was based on the bedrock data (Fig. 2d), and not the bedrock quality data, provided by SGU. This was due to a data gap for this study area, i.e. the bedrock quality map did not cover enough area to provide a reasonable estimation. The bedrock data indicated two types of bedrock around the proposed project: (i) meta-sedimentary rock and (ii) felsic intrusive rock. Comparison with the bedrock quality data for other areas, where SGU classified the quality of the different rocks for use in either concrete, pavement for roads and foundation for railways, indicated that

Table 1 Geological data used for the mass balance estimations

Data	Source[a]	Horizontal resolution	Vertical resolution	Format	Description
Geological data	SGU	1: 50,000	–	Polygon features	Distribution of soils in or near the ground surface as well as the occurrence of blocks. The soils are classified based on formation and grain size composition
Soil thickness data	SGU	10 m	–	Raster	General distribution of soil thickness based on inverse distance weighted (IDW) interpolation
Bedrock data (regional)	SGU	1: 250,000	–	Polygon features	Distribution of rock type and stratigraphical group. The regional bedrock data illustrates the general geological characteristics of the bedrock
Digital elevation model (DEM)	NLSS	2 m	<0.5 m	Raster	The original 2 m DEM from NLSS was resampled to 1 m
Property data	NLSS		–[b]	Polygon features	Property data containing information about buildings, roads and property boundaries, etc.

[a] SGU Geological Survey of Sweden (2013), *NLSS* National Land Survey of Sweden (2013)

[b] Appropriate for visualisation in scale between 1:5000 and 1:20,000

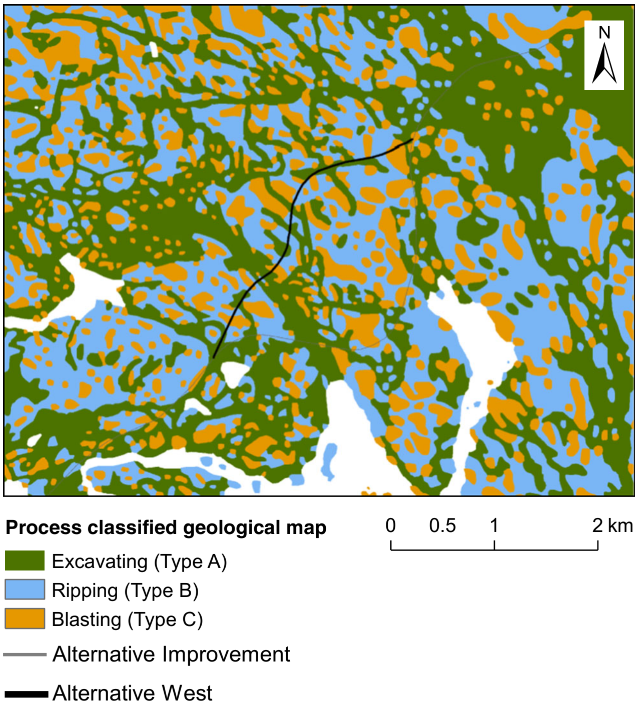


Fig. 5 The three categories used for estimating energy use and GHG emissions were as follows: (i) excavating, (ii) ripping and (iii) blasting

most of the areas where there were felsic intrusive rocks also had the better quality classification than the areas with metasedimentary rocks. Therefore, it was assumed that this also would be the case for this study area. The information about the bedrock quality was used as a base for the mass balance where the volume of "good" quality rock was estimated.

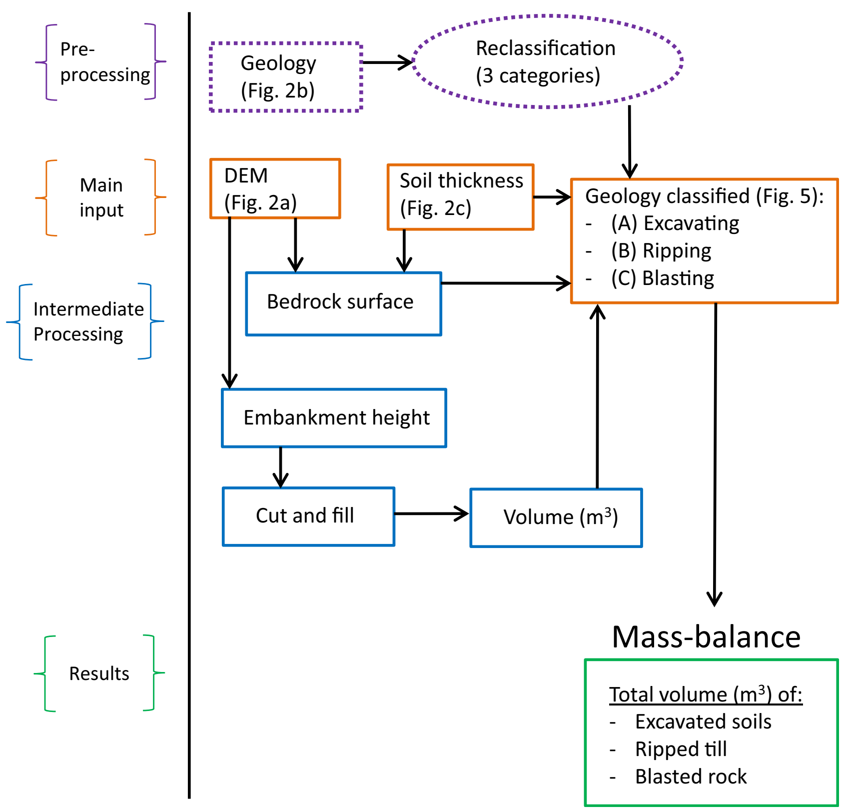
3.2.2 Processing steps

The total volume of excavated soil, ripped till and blasted rock (i.e. mass balance) was estimated using ArcGIS 10 (ESRI 2010) through several modelling steps (Fig. 6). In order to calculate the mass balance, the geological factors (i.e. soil thickness, geology and rock type) were combined with information about the elevation from the DEM along the alternative corridors.

The need to cut or fill was calculated based on the combination of the information regarding the soil thickness along the alternative corridors, the information regarding the specific soil type or location of bedrock outcrops along the corridor surface and the difference between the desired embankment height and the elevation (Fig. 7). The locations where the corridor would pass over bedrock outcrops were assessed in GIS based on the bedrock type in order to retrieve information about the possible quality of blasted filling material.

Information regarding the bedrock surface was retrieved by subtracting the soil thickness from the DEM. The embankment

Fig. 6 The processing steps for the estimation of mass balance in GIS



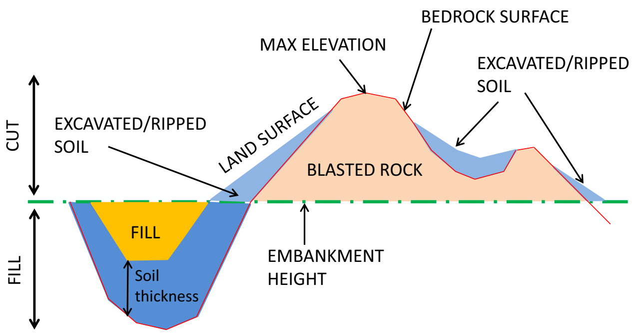


Fig. 7 Cross section indicating the points of cut and fill, alternatively excavating, ripping and blasting

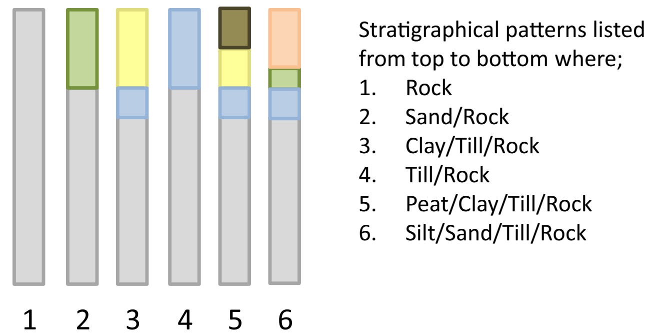


Fig. 8 The six assumed typical stratigraphical patterns

height used in this study for mass balance estimation of both alternatives was assumed to be perfectly horizontal and was set as the average elevation for the already constructed Road Object 55 (37.27 m). The cut and fill depth was calculated by subtracting the embankment height from the elevation, where negative values would indicate the fill depth and positive values the opposite (Eq. 1, Appendix 1). The volume of the cut and fill was then the *cell size of 1 m^2multiplied with the cut and fill depth in meters*. However, in order to estimate the volumes of excavated, ripped and blasted material, seven different processes had to be considered (excavating only, ripping only, blasting only, excavating + blasting, ripping + blasting, ripping + excavating and ripping + excavating + blasting) together with two assumptions. In Assumption 1, the geological stratigraphy was not considered, and the surface soil type was assumed to be continuous until the bedrock surface was reached. In Assumption 2, the geological stratigraphy was considered. The pieces of information regarding soil thickness, bedrock surface and total volumes (m^3) estimated through both assumptions were combined in a spreadsheet using Boolean algebra.

When calculating the mass balance in Assumption 1, only the cut and fill in combination with the surface soil type were of importance (see Eqs. 1–6, Appendix B, Electronic Supplementary Material). However, in order to estimate the volumes of ripped and/or excavated material using Assumption 2, with stratigraphy, six typical patterns were assumed based on expert knowledge (Fig. 8) and patterns found in Jamali et al. 2013:

1. Rock: In the case where the surface consisted of rock outcrops (pattern 1, Fig. 8), there was no soil coverage. In this pattern, blasting or filling could occur but not ripping or excavation. Thus, the volumes of blasted rock were the amounts estimated in Eq. 2 (Appendix B, Electronic Supplementary Material).
2. Coarse grained soils (sand and gravel): In the case where the surface consisted of sand or gravel (pattern 2, Fig. 8), it was assumed that the coarse grained soils would directly overlay the bedrock. Thus, the amount of excavated material would be estimated by using Eq. 3 (Appendix B, Electronic Supplementary Material).
3. Clay: In the case where the surface geology was clay (pattern 3, Fig. 8), it was assumed that the soil underlying the clay would be till followed by bedrock. The ratio between clay and till would be 70/30 where the till could maximum be 2 m thick (see Eqs. 9–9.1; Appendix C, Electronic Supplementary Material).
4. Till: In the case where the surface geology was till (pattern 4, Fig. 8), it was assumed that the till would directly overlay the bedrock. Thus, the amount of ripped material would be estimated by using Eq. 3 (Appendix B, Electronic Supplementary Material).
5. Peat: In the case where the surface geology was peat (pattern 5, Fig. 8), it was assumed that the soil underlying the peat would be clay followed by till and then bedrock. The ratio between the soils would be 35:35:30 and till could maximum be 2 m thick (see Eqs. 10–10.3; Appendix C, Electronic Supplementary Material).
6. Silt: In the case where the surface geology was silt (pattern 6, Fig. 8), it was assumed that the soil underlying the silt would be sand followed by till and then bedrock. The ratio between the soils would be 45:25:30 where sand could maximum be 1 m thick and till could maximum be 2 m thick (see Eqs. 11–11.3; Appendix C, Electronic Supplementary Material).

3.2.3 Life cycle inventory analysis

Life cycle inventory (LCI) factors on energy use and GHG emissions were calculated for the three earthwork categories: soils for excavation (type A), ripping before excavation (type B) and rock for blasting (type C) (Table 2 and Appendix 1). These factors were based on data from the LICCER and the Klimatkalkyl version 2.0 models (Brattebø et al. 2013; Toller and Kotake 2014).

All GHG emission and energy use factors considered direct and indirect impacts. They were calculated per cubic metre of soil or rock that would be moved during road construction.

Table 2 LCI factors used for estimation of energy use and GHG emissions (the estimations were based on data in Appendices 1 and 2)

Processes considered per type of soil	GHG emissions (kg CO_2eq/m^3)	Energy use (MJ/m^3)
Type A (excavation)		
- Emissions from diesel earthworks, simple soil excavation	0.3	4.1
- Emissions from internal transportation of masses from earthworks	0.1	1.3
Total	0.4	5.4
Type B (ripping)		
- Emissions from diesel earthworks, blasted rock	2.5	36.5
- Emissions from internal transportation of masses from earthworks	0.1	1.3
Total	2.6	37.8
Type C (blasting)		
- Emissions from diesel earthworks, blasted rock	2.5	36.5
- Emissions from explosives	2.3	26.3
- Emissions from internal transportation of masses from earthworks	0.1	1.3
Total	4.9	64.1
Filling with soil on-site within the project (Klimatkalkyl 2.0 as in Toller and Kotake (2014))[a]	1.9	27
Filling with rock on-site within the project (Klimatkalkyl 2.0 as in Toller and Kotake (2014))[a]	7.0	98

[a] Klimatkalkyl version 2.0 was the model used as a data source for energy use and GHG emission factors for filling with soil and rock, as this version was the latest model available at the time the approach of this study was developed. There are however small differences in emission factors between this version of the model and the latest versions of Klimatkalkyl (version 3 and version 4), where energy use and GHG emission factors for filling with soil on-site are 29.48 MJ/m^3 and 2.17 kg CO_2/m^3, respectively, and energy use and GHG emission factors for filling with rock on-site are 108.34 MJ/m^3 and 7.96 kg CO_2/m^3, respectively

GHG emissions were expressed in terms of carbon dioxide equivalents ($CO_{2\text{-eq}}$) over 100 years (Goedkoop et al. 2009). The primary energy use was expressed in units of megajoules and considered primary energy carriers including feedstock energy (Huijbregts et al. 2010).

GHG emission and energy use factors for the three earthwork categories were based on the volume of fuel (expressed in litre/m^3) used for moving the masses and of fuel needed for internal transportation of masses within the project. Additionally, explosives used for the blasting of rock were considered for the type C earthwork category (rock for blasting). Diesel was assumed to be the fuel used for transportation of masses. It was also assumed that in case filling was needed according to the resulting mass balance estimation, then firstly all blasted rock would be used as a filling material and secondly the excavated soil would be used. The emission factors are shown in Table 2.

Transport of either imported additional filling material needed for the road construction or the export of surplus material (blasted rock and excavated soil) was excluded from the study. The transport distances for transporting these materials are extremely dependent on other factors such as proximity to other construction projects in the region. Moreover, in reality, no additional filling material from outside of the road construction was imported for the chosen Alternative West (personal communication with Nyman from STA 2014). However, transportation should be included when a complete LCA of road construction is performed. Assuming that surplus material is transported over 10 km (Stripple 2001), rough calculations show that it could generate up to 1.5 kg $CO_{2\text{-eq}}$ per ton of transported material (recalculated after Hammond and Jones (2011)).

3.3 Analysis and comparison of results

Mass balance calculations for both alternatives were compared to the estimates reported in the EIS used during the planning of the road infrastructure (STA 2006). Estimates reported in the EIS were made using AutoCad Novapoint, which is a tool for efficient modelling and design for all types of roads and streets, using on-site measures of elevation (Vianova 2015). Additionally, mass balance estimates for *Alternative West* were compared with actual values obtained after construction of the project was finalised (since *Alternative West* was chosen for construction).

Finally, the estimates of volumes of masses were compared with the volumes of masses calculated using default values (Appendix D, Electronic Supplementary Material) in the Klimatkalkyl model (STA 2015). As mentioned in Section 1, Klimatkalkyl is designed for LCA calculations in early planning and the model contains default values for road construction activities for different road categories (ibid.).

These are based on the data from the road construction project Stockholm Bypass in Sweden (STA 2015). The default values for the following road categories were used in this study: construction of the new 2 + 1 road (which concerns approximately 3 km for *Alternative West*) and widening of the existing two-lane road into a 2 + 1 road (which concerns approximately 3.6 km for *Alternative West* and the whole road stretch (approximately 7.5 km) for *Alternative Improvement*). In the case of soil excavation, rock blasting and filling, the default values in Klimatkalkyl are expressed as cubic metre per kilometre (Appendix D, Electronic Supplementary Material). Thus, in order to estimate the volumes of the materials, the relevant default values were multiplied with the length of the road stretches of the studied alternatives.

4 Results

4.1 Mass balance estimation by a GIS-based approach

Using the GIS-based approach, the length of the road in *Alternative West* was 7.002 km (3.139 km for the new road section and 3.863 km for the extension), while the road length in the EIS was 6.6 km. The GIS-based approach resulted in 38 and 9 % underestimation for cut soils and filling, respectively, compared to the actual values (Table 3). However, for volumes of cut rock, the GIS-based approach resulted in an overestimation of 80 %. Klimatkalkyl applied on the same length as in the GIS-based approach resulted in 1 and 25 % overestimation for cut soils and filling, respectively, compared to the actual values. The volume of cut rock was underestimated by 68 % using Klimatkalkyl. Comparing the EIS with the actual values showed that all values were overestimated. For the volumes of cut soils and filling, the estimates in the EIS were 18 and 20 % larger than the actual volumes. For cut rock, the value was overestimated with 62 %. The mass balance (total cut–fill) in both the GIS-based approach and the EIS were the same (i.e. 55 % overestimation), whereas Klimatkalkyl had a 66 % underestimation compared to the actual mass balance. When using the road length specified in the EIS in Klimatkalkyl, the results were an underestimation of 5 % for cut soils. Filling was overestimated by 18 %, and cut rock was underestimated by 70 %. The mass balance was underestimated by 68 % compared to the actual mass balance. Comparing both Klimatkalkyl estimates (with and without GIS-based road length), it can be noted that the GIS-based road length resulted in a better estimation compared to using default values for cut soils and rock but not for filling.

When taking the stratigraphy (Assumption 2) into consideration, the total estimated volume of cut and fill did not change significantly for both studied alternatives. However,

Table 3 Volumes of excavated soil, ripped till, blasted rock and filling needed, with and without considering stratigraphy, for the studied alternatives (as estimated from the GIS-based model, Klimatkalkyl and STA). The values in the table are rounded off

Volumes for alternatives	GIS-based approach Not considering stratigraphy	GIS-based approach Considering stratigraphy	Estimated in EIS[a]	Klimatkalkyl[b] (using EIS specified road length)	Klimatkalkyl[b] (using GIS specified road length)	Actual values[c]
Alternative improvement						
Cut soils (m^3)	93,500	93,500	184,000	127,100	N/A	N/A
Excavating	14,100	10,100	N/A	N/A	N/A	N/A
Ripping	17,100	21,100	N/A	N/A	N/A	N/A
Filling (m^3)	102,900	102,900	194,000	113,300	N/A	N/A
Cut rock (m^3)	62,300	62,300	50,000	117,900	N/A	N/A
Total	53,000	53,000	40,000	131,700	N/A	N/A
Alternative west						
Cut soils (m^3)	108,600	108,600	207,000	166,300	176,000	174,700
Excavating	58,700	41,300	N/A	N/A	N/A	N/A
Ripping	49,900	67,300	N/A	N/A	N/A	N/A
Filling (m^3)	110,100	110,100	145,000	142,900	151,200	121,000
Cut rock (m^3)	596,100	596,100	535,000	98,700	104,700	330,600
Total (surplus of material)	594,600	594,600	597,000	122,100	129,500	384,300

[a] Estimated by AutoCad Novapoint (STA 2006)

[b] Klimatkalkyl 3.0 Excel model (STA 2015). Klimatkalkyl 3.0 was used for comparison in terms of estimating volumes of blasted rock and soil, as it was the latest developed version by the time this study was finalised. Unlike the previous version of Klimatkalkyl, it contained more data on average volumes for blasted rock and soil for the types of roads used in this study, i.e. road 2 + 1 and widening of a two-lane road (9 m) into 2 + 1 road (14 m)

[c] From STA after construction (personal communication with Nyman from STA in 2014)

there was a small difference concerning the redistribution of masses between the categories excavated soil and ripped soil. In *Alternative West*, the amount of excavated soils decreased by approximately 30 % while ripped soils increased (35 %). For *Alternative Improvement*, the amount of excavated soils decreased by approximately 28 % and ripped soil increased by 23 % when the stratigraphy was considered. In this study, the estimated volume of 'good' quality rock using the bedrock map was approximately 8529 m^3, a substantially lower quantity compared to the need of filling in both alternatives.

Since actual values were not available for *Alternative Improvement*, it was not possible to determine if the estimated values differed significantly from the real values after construction was finished. Thus, it was possible only to compare the estimates for this alternative between the three types of methods considered: the proposed GIS-based approach, estimates provided in the EIS and estimates obtained after using default values in Klimatkalkyl. It was observed that the estimated volumes of cut soils (excavated and ripped) in the EIS for *Alternative Improvement* were almost twice as large as the estimated volumes from the GIS-based approach, while the estimates obtained after using default values in Klimatkalkyl were in between (Table 3). The estimated volumes of blasted rock were relatively similar for the GIS-based approach and EIS, while the estimates based on default values from Klimatkalkyl were almost double than the estimates from the GIS-based approach (Table 3). For the volume of filling material, the GIS-based model estimated almost similar volumes as values obtained after using default values from Klimatkalkyl. However, the estimate of filling in EIS was about 71 % larger in comparison with estimates obtained after using default values in Klimatkalkyl (Table 3).

4.2 GHG emissions and energy use for the studied alternatives

This study developed a spatial approach for showing the LCA results for the studied road alternatives (Fig. 9a, b). The resulting GHG emission and energy use maps (Fig. 9a, b) illustrate the corresponding emissions and energy use in each individual raster cell (1 m × 1 m), as a result from the combination of calculated mass balance (i.e. cut or fill) (Assumption 1) and the LCI factors (Table 2). Thus, the maps show the total energy use and GHG emissions due to soil excavation, rock blasting or filling in each cubic metre of the road stretch.

The maps show that GHG emissions for the start section of *Alternative Improvement* and *Alternative West* were skewed towards filling (i.e. 9.8 kg $CO_{2\text{-eq}}$, Table 4), meaning most construction activities were attributed to filling. This was not unexpected since the elevation was lower in this part of the study area (Fig. 2a) and thus requires filling to reach the assumed embankment height, as well as the use of the already constructed Road Object 55. When passing through an area with rock outcrops, the GHG emissions increased significantly. This was due to the need to blast in order to reduce the elevation to the assumed embankment height. Blasting requires the use of explosives which in turn increases the GHG emissions.

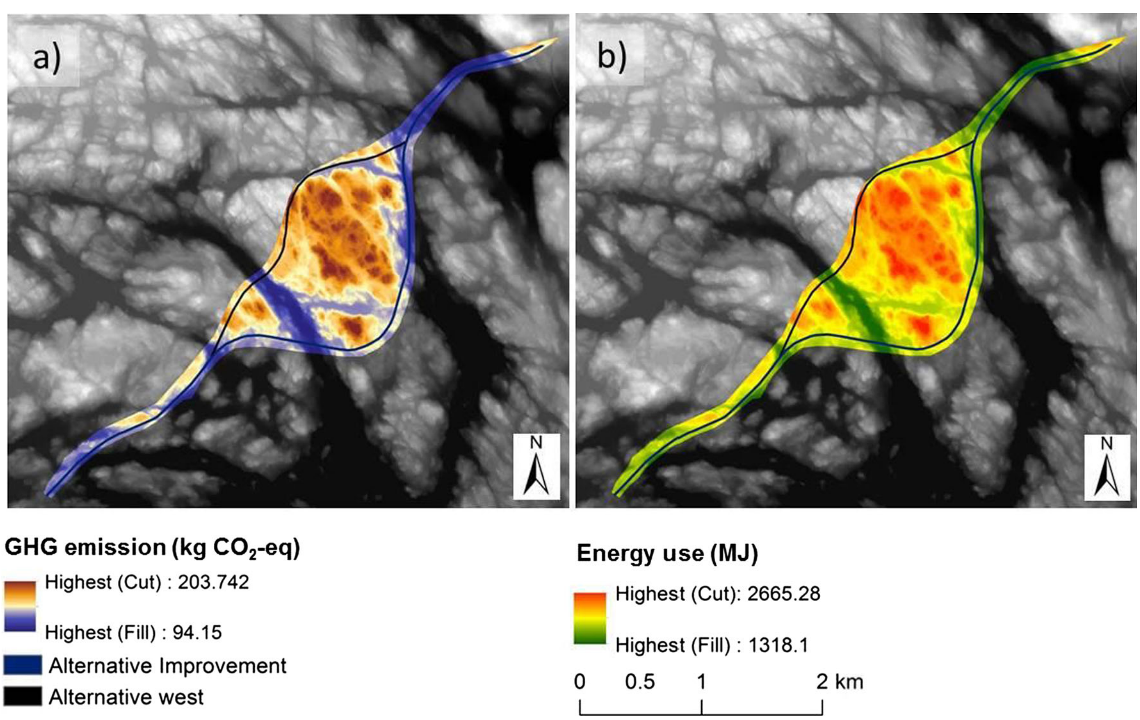


Fig. 9 **a** The estimated GHG emissions for the corridors (in kg $CO2\text{-}_{eq}$). **b** The estimated energy use for the corridors (in MJ). The spatial background is a DEM © Lantmäteriet i2015/920, coordinate system Sweref 99 TM

Table 4 The estimated maximum GHG emissions and energy use for *Alternative Improvement* and *Alternative West* using the GIS-based approach. The total values are rounded off

Alternative corridor	GHG emission (kg $CO_{2\text{-eq}}$)		Energy use (MJ)	
	Cut	Fill	Cut	Fill
Alternative Improvement				
Max (per m^2)	66.3	83.7	867.3	1172.1
Average (per m^2)		9.8[a]		139.3[a]
Total[b]	355,600	513,400	4,718,500	7,204,100
Alternative West				
Max (per m^2)	165.2	83.7	2169.1	1172.1
Average (per m^2)	12.2*		148.8[a]	
Total[b]	3,074,000	770,700	40,411,000	10,790,000

[a] Skewed towards either cut or fill

[b] Total indicates the overall GHG emission or energy use in the whole corridor and is not calculated per square meter

The energy use map (Fig. 9b) showed similarities to the GHG emission map in that the start section of both alternatives contributed to a low energy use, due to the less filling needs because of the use of the already existing road stretch. However, filling with soil on-site (Table 2) contributed to a lower energy use (27 MJ/m^3) compared to filling with rock (98 MJ/m^3), although filling with both materials contributed to higher GHG emissions and energy use than only excavating or blasting. That could be attributed to the energy use and GHG emissions due to crushing of the rock to necessary dimensions for the filling purposes. The energy use increased at sections where rock would be passed similarly to the pattern identified in the GHG emission map. This was not unexpected since an increase in energy use could suggest an increase in the amount of activities undertaken which in turn contributes for instance to higher fuel consumption and thus higher GHG emissions.

When studying the GHG emissions (Fig. 9a and Table 4) for the two evaluated alternatives, it was shown that the GHG emissions for *Alternative Improvement* were overall lower for cutting compared to filling. The average energy use and GHG emission for this alternative were skewed towards filling, meaning most construction activities were attributed to filling. The energy use and GHG emissions for *Alternative West* were larger considering cut only, and skewed towards cutting, compared to *Alternative Improvement*. The same maximum value for energy use and GHG emission attributed to filling could be noted for both alternatives. This was due to the use of the same extension section in the beginning and end of the road for both of these corridor alternatives. Thus, the results show that *Alternative West* has more energy use and GHG emission impacts associated to earthwork activities, in comparison to *Alternative Improvement*.

5 Discussion

5.1 Potential influence of the assumptions on the results

5.1.1 Embankment height and road extension

The differences between the GIS-based estimates and actual volumes could be attributed to the assumed embankment height, width of the road as well as the location of the extension. For instance, an increased embankment height (i.e. causing a smaller difference between the embankment height and the actual elevation) would reduce the amount of blasting required but increase the amount of filling needed. On the other hand, decreasing the embankment height would generate more blasting material and less filling needed. When less filling is needed, the excess blasted material has to be transported off-site, resulting in an increase in the amount of transport with heavy vehicles to and from the construction site as well as an increased risk for accidents. This would then similarly be the case if more filling material would be needed than generated at the construction site, resulting in import of filling material. However, changing the embankment height to either a higher or lower value did not affect the overall slope gradient for *Alternative West*. But if this had been the case, the road stretches with large gradients would have increased the fuel consumption of vehicle transport and cause a negative effect on the environment, such as increased emissions (Vreeswijk and Blokpoel 2013). Therefore, it could be worthwhile to model the embankment height in order to optimise the mass balance, finding the optimal embankment height that would result in cut = fill. From a GHG emission and energy use perspective, the most optimal mass balance must also consider the minimum cut and fill, as well as minimal transport distance and thus fuel use. This implies that deeper cuts and fills need to be avoided, even though the resulting modelled mass balance would be optimal from just a material balance point of view. Mass balance might also not always be the most desirable state. For instance, if there is another project located close that generates large quantities of material that could be used, then it might be better from a GHG emission perspective to use that material in other nearby projects and reduce the need for internal cuttings.

In the process of defining the layers that would be used for mass balance in GIS, it was noticed that the location of Road Object 55 (initial stretch) in the property data from NLSS (Fig. 1) did not fit the location of the road visible in the DEM (Fig. 2a). Assuming that the DEM is more accurate than the property data provided by NLSS, the Road Object 55 as well as the alternative corridors had to be altered to fit the DEM rather than the data from NLSS. The extension of the new road was also assumed to occur by extending 5 m towards the north of the existing Road Object 55, enabling an easier calculation in GIS. In reality, there is a possibility to extend the road sections in different directions, for instance in order to straighten the road or reduce transportation to and from the construction site. Since the details of the road design are not known at an early planning stage, the assumptions in this study were based on simplification. Therefore, there would be differences between the actually removed volumes from *Alternative West* and the estimated volumes using the GIS-based approach.

Moreover, in reality, a bridge was chosen to cross over the valley (Fig. 2a) in *Alternative West*. However, as mentioned in Section 2, the potential use of bridges was not taken into consideration in this study, when using the proposed GIS-based approach (with and without stratigraphy) and Klimatkalkyl. If bridges had been considered, the volumes of blasted material would decrease for the valley as well as the filling required depending on assumed embankment height. The EIS on the other hand did consider the use of a bridge. However, the bridge was only 20 m in length, a small section compared to the overall road length. Therefore, it was assumed that this would have a low impact on the overall estimates reported in the EIS and, consequently, on the comparison with other approaches.

5.1.2 The soil thickness model, stratigraphy and rock quality

The soil thickness and the assumed stratigraphical patterns had an effect on the mass balance estimation. An estimated soil thickness that deviates from the actual depth would either increase or decrease the estimated volumes of material. The soil thickness model used in this study has specified uncertainties (Daniels and Thunholm 2014), where it is noted that areas where there were few input data points to the model would have higher uncertainties than the areas with more data points. This was also the conclusion in Karlsson et al. (2014), where different soil thickness models were developed and compared. Soil thickness can be modelled in different ways, for instance through IDW interpolation or linear regression. Given that there are many different ways of estimating the soil thickness, the implementation of the GIS mass balance modelling approach can be undertaken in several places around the world even though a soil thickness model such as the one provided by SGU is not available. But in order to analyse the errors in the soil thickness, field investigations need to be undertaken, regardless of the used soil thickness model. However, as a preliminary study of alternatives, the soil thickness data from SGU are still useful for general information. As the planning process moves forward, more field investigations should be undertaken in order to improve the model.

In Assumption 1, without considering the geological stratigraphy, the assumption was that the surface soil type was continuous until bedrock surface was reached. In reality, this is not the case when the surface layer consists of a soil type such as clay, silt or peat. Clay is for instance usually deposited on top of till and bedrock. Thus, the estimated volume of ripped and excavated material would be affected in this case. This is also applicable to areas where silt or peat would be the surface soil type. As knowledge about both the stratigraphy and thickness of each soil layer is difficult to retrieve without in situ investigations, general assumptions have to be used if the aim of the study is to derive estimates for an early planning stage. In this study, expert knowledge and general patterns were used as well as estimation of the thickness for each individual soil layer (Fig. 8, Appendix C, Electronic Supplementary Material). Even though the thickness of each soil layer used in Assumption 2 is uncertain, taking the stratigraphy into consideration should improve the accuracy in the mass balance estimation regarding the excavated and ripped materials in the initial planning stage, since it takes the shift between excavated soils (clay, peat and silt) and ripping till into account. A soil thickness map and a proper stratigraphy that is based on field investigations and that accurately represents the subsurface characteristics would further improve the mass balance estimation, thus enabling a more accurate LCA for the proposed project.

In this study, an assumption of rock quality had to be undertaken, since the rock quality data provided by SGU was missing for the study area. Using the rock quality data provided by SGU could potentially improve the mass balance estimation since it could enable an estimation of volumes of ‘good’ quality rock compared to secondary quality rock. During the actual construction of the road in *Alternative West*, all blasted material was reused in the project. This implied that the rock quality of the secondary quality rock group was better than assumed. Rock is heterogeneous and anisotropic, where quality can vary both spatially between locations and within a small area. However, for preliminary planning, the use of a rock quality data can provide an initial understanding of the area and the difference between the alternatives. As the planning process progresses, the need for field investigations increases where verification of the rock quality is necessary, especially if the blasted material is planned to be reused within the project.

5.2 Differences in data used by different LCA models

When comparing the data used in the current study with other models (i.e. Klimatkalkyl 3.0 and Joulesave), certain differences were found in available LCI data for calculation of energy use and GHG emissions from earthworks (excavation of soil and blasting of rock). For instance, the fuel consumption (l/m^3) for type A (soils for excavation) ranged from 0.09 l/m^3 (LICCER, as used in our study) to 0.76 l/m^3 (Klimatkalkyl), an approximate 744 % difference between the highest and lowest values. The fuel consumption for type A soils in Joulesave was 0.18 l/m^3.

One of the reasons for such a big difference could be that different processes were considered for soil excavation. For example, the value in LICCER includes only fuel used for soil excavation (as taken in Stripple (2001)), while the value in Klimatkalkyl includes both soil excavation and loading. Thus, the value for fuel consumption for type A soils used in the LICCER model and in this study is probably underestimated. As a result, due to such big differences across the models, this value should be more accurately estimated through additional case studies.

For type B (soil ripping), the LICCER model had a 100 % higher fuel use (0.8 l/m^3) compared to Joulesave (0.4 l/m^3), whereas data was missing in Klimatkalkyl for this category. It can be noted that LICCER assumed the same fuel consumption for activities associated with soil ripping and rock blasting. The only difference between them was the use of explosives during rock blasting; type C (rock blasting) was not unexpectedly the highest contributor to fuel consumption in LICCER and Joulesave models, as this process involves more fuel consumption for rock blasting activities as well as use of explosives. Klimatkalkyl did not differentiate between the fuel consumption for excavating soil (type A) and rock blasting (type C), even though excavating soils would need less fuel consumption compared to blasting activities. Both the models LICCER and Klimatkalkyl considered the use of explosives for rock blasting, where the use of explosives was 0.5 kg/m^3 in Klimatkalkyl and 1 kg/m^3 in LICCER.

The type of data variability and uncertainty found in different models discussed above is inherent to most LCA studies. As suggested by Heijungs and Huijbregts (2004), several methods can be used for tackling this issue. Some of the most used methods are, for instance, Monte Carlo analysis (calculating a distribution of outcomes by running the model a number of times with randomly selected parameters or parameter values within a certain range) and sensitivity analysis (systematic changing of one parameter while keeping the other parameters constant) (Heijungs and Huijbregts 2004). These types of analysis were not included in the study as they were not considered to be necessary for the purpose of developing and illustrating this approach. Therefore, as in most LCA studies, the results of this study should be interpreted with caution. However, uncertainty analyses should be a part of the future development of our approach, where one of the chosen parameters for testing uncertainty should be data on energy use and GHG emissions from earthworks.

5.3 Potential for coupling of GIS and LCA for road infrastructure planning

When comparing the different approaches for estimation of cut and fill, it was noted that all approaches had difficulties estimating the volumes of cut rock and resulted in a significant over- or underestimation. A reason for the difficulty in estimating the volume of blasted rock could be the assumption that rock is blasted straight down (vertical walls), whereas in reality, rock is blasted in angles, potentially reducing the volumes. All approaches could however quite accurately estimate the volume of filling material and cut soils. The results of this case study showed that using default values from Klimatkalkyl resulted in the best estimates for excavated soils. Thus, using default values from Klimatkalkyl can be a good alternative to GIS-based methods, providing that there are no other data available. However, due to the big variation between projects, it should be emphasised that more case studies should be performed in order to test these approaches in other road construction projects.

It was also observed that even with limitations such as uncertain soil thickness and embankment height, it was possible to estimate the volume of excavated soils, blasted rock and filling needed using the developed GIS-based approach within approximately 38, 80 and 9 % deviation from the actual excavated volumes for *Alternative West*. One reason for this difference could be the location of the road which in this study was slightly altered to fit the DEM, difference in the length of the modelled road (i.e. 7 km, compared to 6.6 km in the EIS) as well as the assumption of a perfectly horizontal embankment following the average elevation. In reality, roads undulate in the terrain both vertically and horizontally. This was as previously mentioned not taken under consideration in this study but could be further elaborated.

In this study, a spatial approach was developed in order to estimate and illustrate the GHG emissions and energy use. With the use of GIS, it was possible to spatially allocate the environmental impacts, i.e. the energy use and GHG emissions, of the excavation, blasting and filling operations (Fig. 9a, b) for each location point of the road corridor alternatives. One advantage of spatial emission mapping is that a comparison between the alternative road corridors as well as surrounding areas can be undertaken. Additional information about the planned road design would increase the accuracy of the estimated values and thus improve the emission estimations. Although additional information is desirable, too detailed information about the road design itself would shift the focus from the preliminary planning stage to the more detailed planning stage, while the aim of the study was to improve the decision support for preliminary road planning. Thus, a GIS-based approach can be a helpful tool during various phases of the life cycle methodology. In particular, in the early phase of planning, when the search for different alternative road corridors is undertaken and the whole landscape is still open for consideration. In this case, the GIS-based approach enables the early evaluation of a wide array of possible alternatives and can be altered to fit the specific project case. The GIS-based approach can also function as a main data inventory as well as for impact assessment and interpretation. As discussed in Geyer et al. (2010), GIS-based models can be regarded as a spatially explicit component within a traditional life cycle inventory model. Bengtsson et al. (1998) also claimed that LCA methodology may become a powerful tool to incorporate and communicate knowledge on environmental issues into various types of decision-making if it is properly designed with respect to geographical information.

6 Conclusions

This study demonstrated how spatial geological data in three dimensions (i.e. length, width and depth) can be used in a GIS environment for the estimation of earthworks during the early stages of road infrastructure planning. Comparing the estimated volumes by the proposed GIS-based approach with the actual values received after one of the alternative road corridors was constructed, it was observed that the estimates for filling material were the most accurate, while the volumes of blasted rock were the most difficult to estimate.

In terms of mass balance estimation, both alternatives resulted in a surplus of material. The use of stratigraphy did not change the total estimated volumes of ripped and excavated material for both alternatives. However, it resulted in a shift between the volumes of ripped and excavated soils. When taking stratigraphy into consideration, the amount of excavated material decreased by about one third for both alternatives. The amount of ripped soils increased by about one fourth and one third for *Alternative Improvement* and *Alternative West*, respectively.

The data on volumes of cut rock, excavated soil and filling material can be used directly during LCA for comparison between road corridor alternatives. Grouping of the excavated soil and blasted rock into three soil types depending on activity performed (excavation, ripping and blasting) was shown to be helpful for estimating GHG emissions and energy use for each location point of the studied road corridors. However, it was found that there is a big variation of data on fuel consumption for each of these activities in different models.

For future work, more data on fuel consumption and its accuracy needs to be analysed in order to improve the spatial mass balance estimation for GHG emissions and energy use. Moreover, additional research is needed on how to incorporate data uncertainty and variation with the help of different approaches, such as sensitivity analysis, Monte Carlo simulations and other. Furthermore, additional information regarding embankment height and soil thickness would further improve the proposed GIS-based approach. The development of a methodology on the consideration of other elements (i.e. bridges, tunnels) in the model could also aid in more accurate estimations of mass balance. The model could also be improved by including potential impacts arising from other processes during road construction that were excluded from this study (i.e. removal of vegetation, soil stabilisation, construction of different layers of the road). In terms of removal of vegetation, the future research should focus both on energy use and GHG emissions from actual activities used to remove vegetation, as well as long-term effects due to loss of carbon sequestration potential and changes in carbon stocks in soil. Expanding the scope further, more research should be done on integration of this model with a more comprehensive assessment during road planning where other environmental, as well as social and economic aspects are considered.

In conclusion, the proposed GIS-based approach shows promising results for usage at an early stage of planning. By providing better data quality, GIS in combination with LCA can enable a fair comparison between road corridor alternatives which could lead to improved planning for a more sustainable transport infrastructure.

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References

Andersen BG, Borns HW (1997) The Ice Age world: an introduction to Quaternary history and research with emphasis on North America and northern Europe during the last 2.5 million years. Scandinavian University Press 82-00-37683-4

Arts J, Lamoen F (2005) Before EIA: defining the scope of infrastructure projects in the Netherlands. J Environ Assess Policy Manage 7:51–80
Azapagic A, Pettit C, Sinclair P (2007) A life cycle methodology for mapping the flows of pollutants in the urban environment. Clean Techn Environ Policy 9:199–214
Bengtsson M, Carlson R, Molander S, Steen B (1998) An approach for handling geographical information in life cycle assessment using a relational database. J Hazard Mater 61(1–3):67–75
Birgisdóttir H (2005) Life cycle assessment model for road construction and use of residues from waste incineration. Technical University of Denmark, Lyngby
Blengini GA, Garbarino E (2010) Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. J Clean Prod 18:1021–1030
Brattebø H, O'Born R, Miliutenko S, Birgisdóttir H, Lundberg K, Toller S, Potting J (2013) LICCER model technical report: account of technical backgrounds of the LICCER model
CEREAL (2014) CEREAL project description
Daniels J, Thunholm B (2014) Rikstäckande jorddjupsmodell (in Swedish) (nationwide soil depth model), SGU rapport No. 2014: 14, Geological Survey of Sweden
Dresen B, Jandewerth M (2012) Integration of spatial analyses into LCA-calculating GHG emissions with geoinformation systems. Int J Life Cycle Assess 17:1094–1103
EC (2012) Environmental assessment
EC (2013) Guidance on integrating climate change and biodiversity into environmental impact assessment
ECRPD (2010) Energy conservation in road pavement design, maintenance and utilisation
ESRI (2010) ArcGIS (version 10) [GIS application]. Environmental Systems Research Institute, Inc., Redlands
Flint FR (1971) Glacial and quaternary geology. John Wiley and Sons Inc. 0-471-26435-0
Garbarino E, Quintero RR, Donatello S, Wolf O (2014) Revision of green public procurement criteria for design, construction and maintenance of roads, technical report, working document for the 2nd Ad-Hoc Working Group meeting, European Commission, Joint Research Centre
Gasol CM, Gabarrell X, Rigola M, González-García S, Rieradevall J (2011) Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale. Biomass Bioenerg 35:2975–2985
Geological Survey of Sweden (2013) http://www.sgu.se. Accessed 12 March 2016
Geyer R, Stoms DM, Lindner JP, Davis FW, Wittstock B (2010) Coupling GIS and LCA for biodiversity assessments of land use. Int J Life Cycle Assess 15:454–467
Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Zelm, Rv (2009) ReCiPe 2008, PRé Consultants, University of Leiden, Radboud University Nijmegen, RIVM
Hammervold J, Reenaas M, Brattebø H (2009) Environmental effects—life cycle assessment of bridges. TKK Structural Engineering and Building Technology, Espoo
Hammond, G, Jones, C (2011) A BSRIA guide: embodied carbon. The inventory of carbon and energy (ICE)
Heijungs R, Huijbregts MAJ (2004) A review of approaches to treat uncertainty in LCA, international environmental modelling and software society. University of Osnabrück, Germany
Huijbregts MAJ, Hellweg S, Frischknecht R, Hendriks HWM, Hungerbuhler K, Hendriks AJ (2010) Cumulative energy demand as predictor for the environmental burden of commodity production. Environ Sci Technol 44:2189–2196
ISO 14044 (2006) Environmental management—life cycle assessment—requirements and guidelines
Jamali AI, Olofsson B, Mörtberg U (2013) Locating suitable sites for construction of subsurface dams using GIS. Environ Earth Sci 70: 2511–2525
Karlsson CSJ, Jamali IA, Earon R, Olofsson B, Mörtberg U (2014) Comparison of methods for predicting regolith thickness in previously glaciated terrain, Stockholm, Sweden. Geoderma 226–227:116–129
Kluts I, Miliutenko S (2012) Overview of road infrastructure planning process and the use of environmental assessments in the Netherlands and Sweden . KTH, Environmental Strategies Research, Stockholm2012:6
Liljenström C (2013) Life cycle assessment in early planning of road infrastructure—application of the LICCER-model, KTH
Loorents K-J (2006) Bergmaterial i väglinjen (in Swedish) (Rock material in the road alignment), VTI
Miliutenko S, Kluts I, Lundberg K, Toller S, Brattebø H, Birgisdóttir H, Potting J (2014a) Consideration of life cycle energy use and greenhouse gas emissions in road infrastructure planning processes: examples of Sweden, Norway, Denmark and the Netherlands. J Environ Assess Policy Manage 16:26
Miliutenko S, Liljenström C, Brattebø H, Birgisdóttir H, Toller S, Lundberg K, Potting J (2014b) Life cycle impacts during early stages of road infrastructure planning: a case study in Sweden. Transport Research Arena 2014, Paris
National Land Survey of Sweden (2013) Teknisk fakta (In Swedish) (Technical data)
Shamoon H (2012) Energieffektiv vägdesign (in Swedish) (Energy efficient road design). KTH, Stockholm
STA (2006) Väg 55, delen Yxtatorpet–Malmköping Vägutredning Samrådshandling 2006–01-25 (in Swedish) (Highway 55, part Yxtatorpet-Malmköping Road Feasibility Study Consultation Document). Objekt nr 10898
STA (2011) Environmental impact assessment: roads and rail. Swedish Transport Administration, Publication No 2011:155
STA (2014) Väg 55, Yxtatorpet − Malmköping, mötesfri landsväg (in Swedish) (Yxtatorpet − Malmköping, dual carriageway). Swedish Transport Administration
STA (2015) Klimatkalkyl- infrastrukturhållningens energianvändning och klimatpåverkan i ett livscykelperspektiv, Riktlinje, TDOK 2015:0007 (in Swedish) (Klimatkalkyl—energy use and climate impact of infrastructure in a life cycle perspective, Guideline, TDOK 2015 0007). http://www.trafikverket.se/tjanster/system-och-verktyg/Prognos–och-analysverktyg/Klimatkalkyl/. Accessed 12 March 2016
STA (2016) Metodbeskrivning Geokalkyl väg - tidiga skeden Version 2. 2016-02-01 (in Swedish) (Method decsription Geokalkyl road - early stages Version 2). Swedish Transport Administration. http://www.trafikverket.se/contentassets/b68d4ee835484812a9236db2f849439a/metodbeskrivning_geokalkyl_vag_tidiga_skeden_2.pdf. Accessed 23 Dec 2016
Straume A (2011) Dokumentasjon av modul for beregning av energiforbruk og klimagassutslipp i EFFEKT (in Norwegian) (Documentation of the module for calculating the energy consumption and greenhouse gas emissions in EFFEKT). SINTEF Notat, Trondheim
Stripple H (2001) Life cycle assessment of road. A pilot study for inventory analysis. Gothenburg
Toller S, Kotake M (2014) Klimatkalkyl version 2.0—Beräkning av infrastrukturens klimatpåverkan och energianvändning i ett livscykelperspektiv (in Swedish) (Klimatkalkyl version 2.0—calculation of the infrastructure's impact on climate change and energy use in a life cycle perspective), Trafikverket
van't Wout F, Groot M, Sminia M, Haas M (2010). Functionele Specificatie DuboCalc (in Dutch) (Functional specification DuboCalc). Document nr NWP0800100-FS
Vianova (2015) Novapoint Väg Bas
Vreeswijk J, Blokpoel R (2013) Fuel and emission factors—how much can we realistically reduce with ITS? 9th ITS European Congress. TP0049, Dublin, Ireland